PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

The Effect of the Weld Type on Ensemble Average in SEA

Paweł Nieradka[1]; Sebastian Szarapow[1]

[1] KFB Acoustics sp. z o. o., Poland

ABSTRACT

Statistical energy analysis (SEA) predicts the average response of a population. This population consists of similar vibroacoustic structures subjected to white noise forces at high frequencies. However, usually in engineering applications, the SEA method is used to determine the response of a particular structure. It results from the assumption, that in the case of complex structures the response of a single member from the population will not significantly differ from the average. The aim of the research was to check the above assumption on a simple structures. Six similar mechanical structures were tested. Each structure consisted of two plates welded together at right angles. The vibration (velocity) level reduction between the plates was determined. From the point of view of the SEA, each of the six L-shaped structures is represented by the same SEA system composed of two 2D subsystems connected by line junction. However, the resulting line junctions have been achieved by two different welding techniques. This detail is omitted during SEA calculations. Vibration reduction obtained on a single structure was compared with ensemble average covering the entire six-element sample. The influence of the weld type on transmission was considered. The obtained results were compared with the SEA prediction.

Keywords: SEA, Transmission, Junctions

1. INTRODUCTION

The energy of the bending waves is directly related to the radiated acoustic power. Therefore, the ability to predict bending wave transmission in structures is an important aspect of noise and vibration control. Structures of great practical importance, which are the object of numerous studies, are steel constructions. Steel constructions commonly found in mechanical engineering often consist of welded plates. Hence there is a strong need to predict energy transmission in such systems.

The Statistical Energy Analysis (SEA) is a popular tool for conducting vibroacoustic simulations in the high frequency range. The basic parameter used in SEA simulations is called Coupling Loss Factor (CLF), which describes subsystem losses resulting from energy flow to another subsystem. Welded joints are often approximated by line junctions for which there exists a theoretical CLF formula. The work will investigate the influence of the geometry of the applied welds on the transmission of bending waves. This effect is not included in the basic formula for the simple line connection and can be considered in the context of ensemble average. Using the SEA method, one obtain results averaged within similar structures (ensembles). This means, that SEA results are only approximations when they are associated with a specific structure (1). Six structures (SEA systems) were tested in the work. Each system consisted of two steel plates (subsystems) connected at right angles. There were the following differences between the systems:

a) different arrangement of the plates during welding,
b) different location of the weld.

In the further part of the work it will be checked whether the introduced changes have a significant impact on the transmission of vibrations and whether all six systems can be assigned to one set called "structures similar to one another".

[1] p.nieradka@kfb-acoustics.com

2. THEORY

2.1 Coupling Loss Factor of Line Junctions

The Coupling Loss Factor of line-coupled 2D subsystems is determined from (1):

$$\eta_{12} = \frac{Lc_{g1}}{\pi\omega S_1}\tau_b \tag{1}$$

where c_{g1} is wave group speed of subsystem 1, L is length of connection, ω is angular frequency, S_1 is the surface area of the first subsystem, τ_b is bending wave transmission coefficient averaged over the angle of incidence. As one can see, the CLF coefficient is directly proportional to the transmission coefficient. In the literature, one can find formulas for the transmission coefficient assuming rigid plate connection (3) and models allowing to take into account the finite stiffness and resistance of the joints (4, 5). The transmission coefficient was determined in the present study based on the model shown in (4). Mechanical parameters of the weld were also assumed as in (4): stiffness was set to 100 GN/m and damping was set to 1.8 kNs/m.

2.2 Statistical Energy Analysis of Two Coupled Plates

The SEA method allows to determine the average mechanical energies of subsystems, E, by solving a system of linear equations, where the column of free words are average input powers, and the main matrix is formed by DLF and CLF (2). In the case of two coupled plates, the SEA model comes down to the solution of the following system:

$$2\pi f \begin{pmatrix} \eta_1 + \eta_{12} & -\eta_{21} \\ -\eta_{12} & \eta_2 + \eta_{21} \end{pmatrix} \begin{pmatrix} E_1 \\ E_2 \end{pmatrix} = \begin{pmatrix} P_1 \\ P_2 \end{pmatrix} \tag{2}$$

where f is frequency in Hz, η_1 and η_2 are damping loss factors (DLF), η_{21} and η_{12} are coupling loss factors (CLF) computed as shown in 2.1. After solving the system of equations (2), the average square of vibration velocity of the subsystem with the mass M can be determined from the equation:

$$v^2 = E/M. \tag{3}$$

Statistical Energy Analysis works best if modal overlap M_o is greater than unity (6):

$$M_o = n\eta\omega > 1 \tag{4}$$

where n is asymptotic modal density:

$$n = S\omega/(2\pi c_g c_f). \tag{5}$$

In equation (5) c_g is subsystem group speed, c_f is phase speed, S is the area of the plate.

In addition, the subsystems should be weakly coupled. The coupling strength can be estimated based on the parameter γ_{ij}:

$$\gamma_{ij} = \eta_{ij}/\eta_i. \tag{6}$$

Coupling is assumed to be weak, if $\gamma_{ij} \ll 1$ condition holds.

3. MEASUREMENTS

3.1 Tested Objects

The research objects were six mechanical constructions. Each construction consisted of two steel plates welded at right angles. The structures during the measurements were freely suspended on the strings (two anchor points were placed on each plate). Each plate was assigned a number from 1 to 12, which was used to identify them. The mechanical and geometric parameters of the plates are summarized in Table 1. Internal losses of plates can be found in section 4.2.

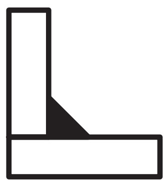
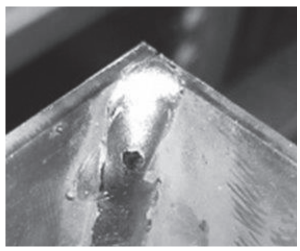
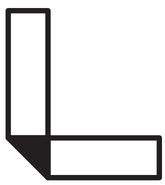
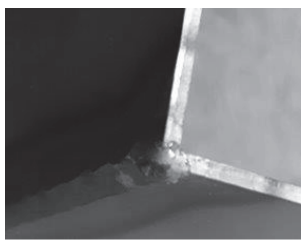
Table 1 – Parameters of plates

Parameter	Value
Length, L	0.49 m
Width, W	0.49 m
Thickness, h	0.002 m
Density, ρ	7884 kg/m^3
Young Modulus, E	200 GPa
Poisson Number, σ	0.3

3.2 Types of Junctions

The individual pairs of plates have been coupled together using one of two joints: Weld A and Weld B. Differences between welds are shown in Table 2. Welds were made using MAG (Metal Active Gas) technique.

Table 2 – Types of tested welds

Junction	Pairs of plates	Geometry	Photo
Weld A	12-1, 2-3, 4-5		
Weld B	6-7, 8-9, 10-11		

3.3 Damping and Coupling Loss Factors

The work concerns the transmission of bending waves, that is why the components of the velocity vector perpendicular to the plate are considered. Before merging of plates, measurements of internal losses (η, DLF) by the structural reverberation time were carried out:

$$\eta = 2.2/(RT_{60} \cdot f) \tag{7}$$

where RT_{60} is structural reverberation time

The plates were then joined and a further series of measurements was carried out. Mechanical power was injected at individual points selected on the plates using the vibration exciter. Each plate was excited in three randomly selected places. Then, for each excitation, the average mechanical velocity was determined on the source and receiver subsystem (on each plate the signal was picked up using accelerometers in six randomly selected places). Excitation of the plate in many places and averaging of individual responses approximates the "rain-on-the-roof" excitation, which is one of the assumptions of the SEA method. The energy ratios of the receiver and source plates have been determined. Additionally, TLF (Total Loss Factor) measurements were taken based on the structural reverberation time of the entire structure to determine CLF and DLF using the Energy Ratio Method (7). The system during measurements is shown in Figure 1.

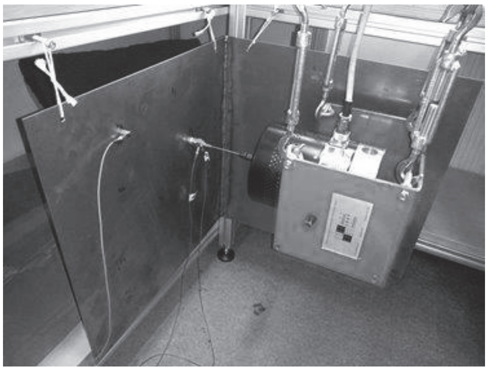


Figure 1 - Plate 2 excited at point 1. Response measured on Plate 2 at point 3

In order to determine DLF (η_1, η_2) the system of equations was solved, where the main matrix consisted of the energy ratios e_{ij} (receiver plate i to the source plate j), while the column of free words contained the measured TLF (η_{1t}, η_{2t})

$$\begin{pmatrix} 1 & e_{21} \\ e_{12} & 1 \end{pmatrix} \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} = \begin{pmatrix} \eta_{1t} \\ \eta_{2t} \end{pmatrix}. \tag{7}$$

Using the results from (7) the second system of equations was solved, allowing to determine the CLF coefficients (η_{12}, η_{21})

$$\begin{pmatrix} 1 & -e_{21} \\ -e_{12} & 1 \end{pmatrix} \begin{pmatrix} \eta_{12} \\ \eta_{21} \end{pmatrix} = \begin{pmatrix} e_{21}\eta_2 \\ e_{12}\eta_1 \end{pmatrix}. \tag{8}$$

4. RESULTS

4.1 Comparison of Welds

Figure 2 presents the averaged Velocity Level Difference D for welds A and B. Energy ratios from which the results can be determined are listed in table 3.

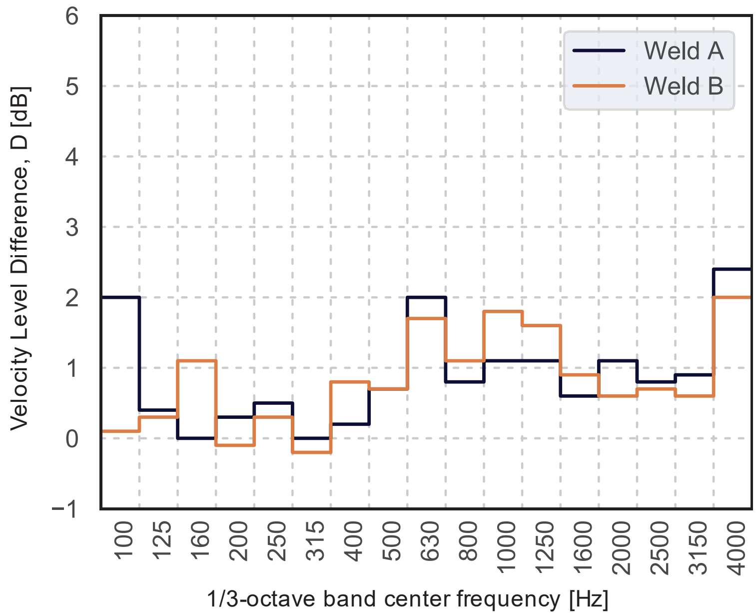


Figure 2 - Measurement results for welds A and B

In order to determine if there is a difference in energy transmission using welding A or B, the results of the measurements were divided into two groups. The first group (the representation of the population of plates with weld A) has been assigned six parameters determined from the relationship:

$$e_{A,i} = \frac{E_{source,A,i}}{E_{receiver,A,i}}; \qquad i = 1, 2, \dots, 6 \tag{9}$$

Similarly, six parameters were assigned to the second group (representation of the plate population with weld B):

$$e_{B,i} = \frac{E_{source,B,i}}{E_{receiver,B,i}}; \qquad i = 1, 2, \dots, 6 \tag{10}$$

where $E_{source,X,i}$ – spatially averaged energy of the source system for joint X (sample i), $E_{receiver,X,i}$ – spatially averaged energy of the receiver system for joint X (sample i). The size of individual groups is 6, because for a given structure two energy ratios have been determined by exchanging the source and receiver plates. It is worth noting that definitions (9) and (10) have the energy of the receiving system in the denominator, that's why they are the inverse of parameters from the main matrix in equations (7) and (8). Then, the Welch's t-test at 0.05 significance level was conducted to check the following null hypothesis H_0: The average mechanical energy ratio of the source and receiver plate is independent of the type of weld used. Table 3 shows the determined average energy ratios for each weld type, standard deviations σ and test results.

Table 3 – Results of two-tailed Welch's t-test

f [Hz]	$\bar{e_A}$ (σ_{e_A})	$\bar{e_B}$ (σ_{e_B})	t	$t_{0.05}$	f [Hz]	$\bar{e_A}$ (σ_{e_A})	$\bar{e_B}$ (σ_{e_B})	t	$t_{0.05}$
100	1.60 (0.85)	1.02 (0.17)	1.63	2.51	1000	1.30 (0.23)	1.52 (0.36)	1.24	2.28
125	1.09 (0.20)	1.08 (0.06)	0.13	2.46	1250	1.29 (0.25)	1.44 (0.69)	0.50	2.42
160	1.01 (0.12)	1.29 (0.30)	2.13	2.40	1600	1.15 (0.17)	1.22 (0.13)	0.79	2.25
200	1.08 (0.25)	0.97 (0.11)	0.98	2.38	2000	1.27 (0.15)	1.15 (0.11)	1.65	2.25
250	1.13 (0.09)	1.07 (0.12)	0.94	2.25	2500	1.20 (0.20)	1.17 (0.27)	0.19	2.25
315	0.99 (0.09)	0.95 (0.03)	1.08	2.42	3150	1.23 (0.19)	1.14 (0.16)	0.86	2.24
400	1.04 (0.13)	1.19 (0.07)	2.38	2.32	4000	1.73 (0.66)	1.60 (0.16)	0.46	2.49
500	1.17 (0.16)	1.18 (0.11)	0.11	2.26					
630	1.59 (0.20)	1.46 (0.34)	0.77	2.30					
800	1.20 (0.35)	1.28 (0.11)	0.55	2.44					

For each 1/3-octave band center frequency f (except for 400 Hz), the calculated statistic t is less than the critical statistics $t_{0.05}$ at 0.05 significance level (two tailed test). Therefore, there is no reason to reject the null hypothesis. Only for the 400 Hz, the null hypothesis can be rejected. However, for 400 Hz, the observed difference between D for welds A and B is only 0.6 dB and in practice, this difference can be neglected.

4.2 CLF and DLF measurement

The results averaged for all six structures will be considered in the further part of the work, because in point 4.1 no differences between welds A and B have been proven. Figure 3 shows the DLF determined on the disconnected plates, DLF determined by the ERM method (on joined plates), CLF determined by the ERM method and CLF determined from the theoretical formula (1). During measurement, few CLF values were negative for some measuring points. Such cases can occur when the SEA system assumptions are not met. Negative values have been omitted in the course of the calculations because they are contradictory in the classic SEA approach.

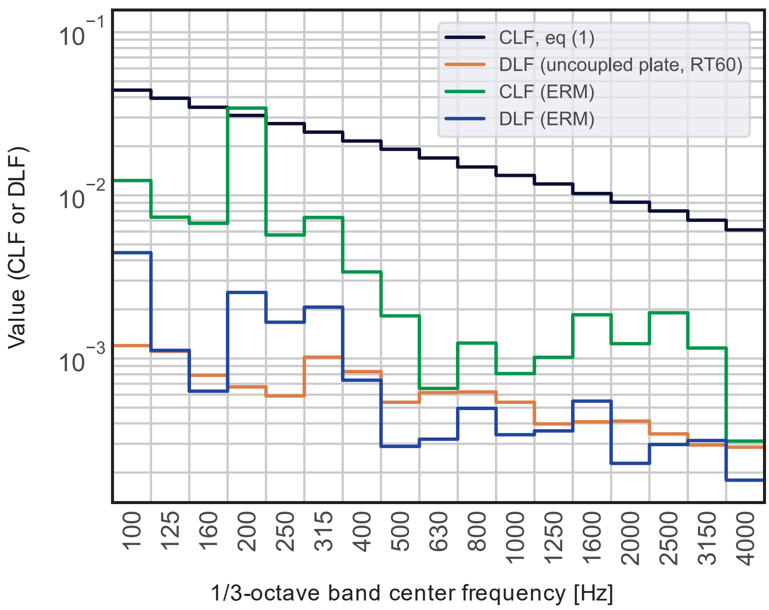


Figure 3 – Coupling Loss Factors and Damping Loss Factors

The DLF and CLF parameters determined by the ERM method were compared with each other using the relationship (6) to check the coupling strength. Additionally, a modal overlap was designated using (4). The smallest value of parameter γ_{ij} occurred for 4000 Hz and was equal to 1.74. The largest modal overlap value (0.04) occurred at 3150 Hz. Thus, it can be seen that in the whole considered frequency range, the tested plates do not meet the assumptions of SEA.

A small value of the modal overlap parameter explains the occurrence of smaller measured CLF values in relation to the theoretical ones. It also explains the results from point 4.3, where a higher value of D was observed in relation to the theory. In this situation, not all modes are excited evenly and only a few vibration modes are responsible for energy transmission, and the share of the other modes is insignificant (8).

4.3 SEA Simulation

Figure 4 shows the simulated (SEA) and measured (averaged for all structures) velocity level difference D between plates. The obtained results correspond to the differences observed between coupling loss factors from figure 3. The greater theoretical value of the CLF factor is reflected in the form of very small values of the simulated D. The analysis of the chart in Figure 4 clearly shows that, from the point of view of the SEA, the division of the system in question into two subsystems is unfounded. This means that indicators such as modal overlap and γ_{ij} fulfilled their role.

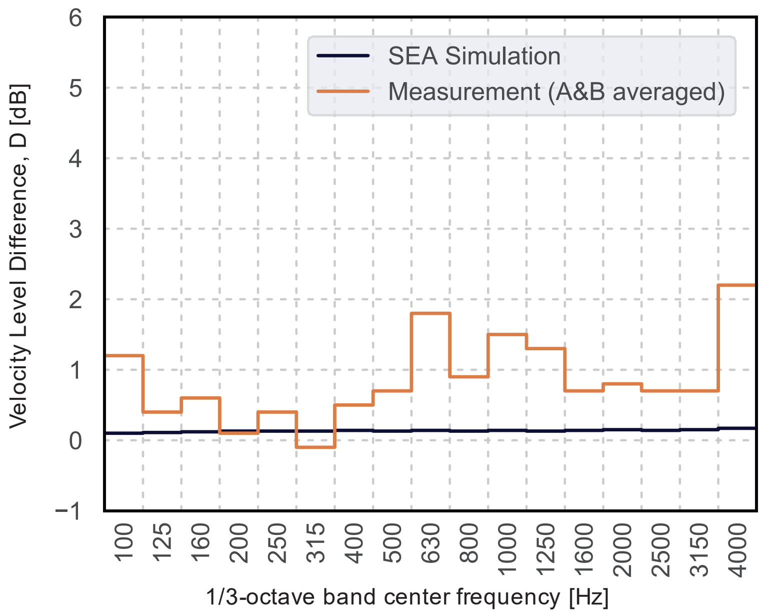


Figure 4 – SEA simulation results vs averaged measurement results

5. CONCLUSIONS

When we consider ensemble average, we may allow subsystems with different weld types to be included in averaging process, because there was no difference in vibration transmission when using different welds. Only for 400 Hz, a statistically significant difference was found between welds A and B. However, the difference in transmission for 400 Hz is small (0.6 dB) and in practical applications may be ignored.

Differences between the DLF parameters determined by the ERM method (joined plates) and the reverberation time method (disconnected plates) were observed. Differences may result from the inaccuracy of the measurement methods and the influence of the joint on the overall system damping.

The plates in the tested system were not weakly coupled and the modal overlap was less than one. Under such conditions, not all modes are excited evenly and only a few vibration modes are responsible for the energy transmission between subsystems (the contribution of the other modes is negligible). This phenomenon causes that the SEA method (which assumes the even excitation of all modes) predicts higher transmission (smaller velocity level difference, higher coupling loss factor) than the measurement results indicate. In such situations, other simulation methods like SmEdA (8) may provide better results.

ACKNOWLEDGEMENTS

Financial support for this research from KFB Acoustics sp. z o.o. is gratefully acknowledged. We would like to send special thanks to Patryk Kobyłt, Marek Dwornik and Bartosz Chmielewski for technical support during the project.

REFERENCES

1. Le Bot A. Foundations of Statistical Energy Analysis in Vibroacoustics. 198 Madison Avenue, New York, USA: Oxford University Press; 2015.
2. Lyon RH, DeJong RG. Theory and Application of Statistical Energy Analysis. Newton, Massachusetts, USA: Butterworth-Heinemann; 1995.
3. Cremer L, Heckl M. Structure-Borne Sound (2nd edition). Berlin, Germany: Springer-Verlag; 1988.
4. Patil VH, Manik DN. Determination of coupling loss factors (CLF) for right angled plates. Proc ICSV22; 12-16 July 2015; Florence, Italy 2015.
5. Leung R, Pinnington R. Wave propagations through right angle joint with compliance-flexural incident wave. Journal of Sound and Vibration. 1990;142:31-46.
6. Le Bot A, Cotoni V. Validity diagrams of statistical energy analysis. Journal of Sound and Vibration. 2010;329:221-235.
7. Cuschieri JM, Sun JC. Use of Statistical Energy Analysis For Rotating Machinery, Part I: Determination of Dissipation and Coupling Loss Factors Using Energy Ratios. Journal of Sound and Vibration. 1994;170:181-190.
8. Maxit L, Guyader JL. Extension of SEA model to subsystems with non-uniform modal energy distribution. Journal of Sound and Vibration. 2003;265:337-358.